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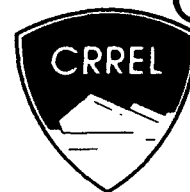
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Three Approaches to Winter Traction Testing

Sally A. Shoop

July 1993



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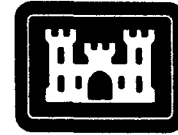
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Abstract

Traction on winter surfaces was measured using three test vehicles, each designed to measure traction for a different purpose: vehicle mobility research (CRREL Instrumented Vehicle), commercial tire testing (Uniroyal-Goodrich traction tester), and airport runway safety (Saab friction tester). The traction measured with each method is comparable, but there are systematic differences due to the effects of the surface material and the test and analysis technique. This comparison serves as the fundamental basis for collaboration between the various traction testing communities and illustrates the need for well documented test procedures and data analysis as a standard for traction testing and evaluation.

Cover: Left to right: The Saab friction tester with driver Mark Lucier, the Uniroyal-Goodrich traction tester with driver Jack Davis, and the CRREL Instrumented Vehicle with driver Byron Young.

For conversion of SI metric units to U.S./British customary units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-89a, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.



**US Army Corps
of Engineers**

Cold Regions Research &
Engineering Laboratory

Three Approaches to Winter Traction Testing

Sally A. Shoop

July 1993

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

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PREFACE

This report was prepared by Sally A. Shoop, Research Civil Engineer, of the Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The project was funded by DA Project 4A762784AT42, *Design, Construction, and Operations Technology for Cold Regions*; Task CS, Work Unit 007, *Off-Road Mobility in Thawing Soils*.

This work would not have been possible without the cooperation and assistance of Jack Davis, Testing Services and Instrumentation Co., Engineering Consultant operating the Uniroyal-Goodrich traction tester; Russell Alger, Group Leader, Snow Research Institute, Keweenaw Research Center, providing the Saab and the snow data; Byron Young, Technician and operator of the CRREL Instrumented Vehicle, who collected and reduced the CIV data; and Paul Richmond, who assisted with the CIV during the winter of 1993. The author is also grateful to Mark Lucier for his assistance in operating the Saab friction tester; Michelin Americas Research and Development Corporation, owners of the Uniroyal-Goodrich traction tester; Paul Richmond and George Blaisdell for reviewing the paper; Maria Bergstad for editing; and William Bates and Thomas Vaughan for drafting the figures.

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Three Approaches to Winter Traction Testing

SALLY SHOOP

INTRODUCTION

Traction of tires or other running gear on different surfaces can be measured in many different ways with widely varied equipment (i.e., single wheel testers, fixed slip testers, drawbar tests, and instrumented vehicles). Before the 1970s, vehicle traction was generally measured by performing a drawbar pull test, where the amount of pull a vehicle could produce was measured using a load cell attached to the rear of the vehicle. With advances in electronics, drawbar tests have been augmented by new testing equipment where traction is measured at each individual wheel and tests can be computer controlled. This enables the traction equipment and technique to be designed specifically for each test purpose.

For testing the traction qualities of new tire or tread designs, the Uniroyal-Goodrich (U-G) traction tester is equipped to measure efficiently or rapidly the traction of many different tire classes. To assess friction on a runway surface for safe aircraft landing, the Saab friction tester is designed to measure traction at a fixed value of braking slip using a scaled airplane tire. For vehicle traction and mobility research, the CRREL Instrumented Vehicle (CIV) is capable of performing a variety of mobility tests (traction, resistance, maneuverability) using different tires, traction aids, and vehicle configurations on a wide range of terrain surfaces. Although other traction test devices exist, these vehicles represent well-known, state-of-the-art equipment for three major traction testing communities. The test procedure and data analysis are different for each vehicle; each is designed for optimum operation for its specific purpose.

To tap the resources and experience of each of these three traction measurement groups, a comparison of test method and data reporting was performed. The three vehicles were used to measure traction in side-by-side tests on surfaces typical of

winter environments including ice, snow, and asphalt runway surfaces. We compare these traction test vehicles, point out some of the differences in the collection, reduction, and reporting of traction, and establish a basis for comparison and future collaboration among the various traction testing communities.

TRACTION TEST METHODS

For each surface tested, the vehicles traversed the same distance, one after the other, operating beside the wheel path of the previous vehicle. The speed of the vehicles was held at 8 km/hr (5 mph) in accordance with the speed range specified by SAE (1985). (This is the normal test speed of the CIV and the U-G, but the Saab normally measures friction at a base vehicle speed of 64 km/hr.) Although the three traction test vehicles measure traction in the same basic way, using a torque or load cell on one or more instrumented wheels, the design and operation of each vehicle differs according to its purpose. Details of the instrumentation of each of the vehicles as well as samples of their graphic output are provided in Appendix A.

Saab friction tester

The Saab measurement of braking traction correlates well with the actual braking ability of aircraft (Yager et al. 1988). At the rear of the vehicle is an instrumented fifth wheel that is lowered to contact the pavement at a set vertical load (Fig. A1). The wheel is geared to operate at an angular velocity that is lower than that of the drive wheels. This results in a continuous 12% braking slip, and the consequent axle torque is measured and converted to a friction coefficient. The standard test tire is a Friction Tester AERO 4.00-8 in. made of natural rubber (shore hardness 60) with circumferential grooves, simulating an aircraft tire (Table 1).

The friction and vehicle speed are recorded and

Table 1. Tire characteristics.

	<i>CIV and U-G</i>	<i>Saab</i>
Design	All-season radial, mud and snow	Aircraft tire with circumferential grooves
Tire size	LT 235/75 R 15	4.00- x 8-in.
Tread width	15.7 cm	5.5 cm
Inflation pressure	180 kPa	700 kPa
Normal load	6200 N	1400 N
Contact area	364.5 cm ²	31.6 cm ²

plotted every meter. For this study, the friction was measured over a distance of 121 m (400 ft) and averaged every 33.3 m (100 ft) as shown in Figure A2. This test setup was repeated three times for each surface.

Uniroyal-Goodrich traction tester

The U-G traction tester measures the driving traction of tires in snow for the tire and automobile industry. It is fully automated to measure traction at one instrumented wheel and is designed for performing numerous tests quickly. The vehicle is a rear-wheel-drive Chevrolet C-10 one-half-ton pickup truck. The right rear axle is instrumented with an orthogonal load cell to measure the fore-aft and vertical forces on the tire. The rear of the truck has a weight system for adjusting the vertical load on the back axle, as well as an automated, self-contained jacking unit and a special wheel retention system (knock-off hub) for increasing the ease and speed of testing numerous tires (Fig. A3).

Traction tests are conducted by increasing the driving torque to the test wheel while maintaining constant vehicle speed (8 km/hr) by braking the other wheels. The torque is increased gradually using an automatic throttle, until the desired maximum tire spin is achieved. Generally, 10 spinups are conducted in a single pass over the test section. In each spinup, traction is measured over a range of wheel slips covering a distance of approximately 10 m. The full traction-slip curve is recorded for each spinup and then averaged over the 10 spinups (Fig. A4). For commercial tire testing (SAE 1985), this test sequence is performed three times, each on a different day. An average of the traction coefficient over a specified range of slip or Differential Interface Velocity (DIV) is then calculated for comparison among tires.

The Uniroyal-Goodrich tester was configured with the same tire as the CIV for the comparison tests: a standard mud and snow radial (Table 1).

CRREL Instrumented Vehicle

The CIV differs from the U-G tester in that all four wheels are independently instrumented (Fig. A5 and A6) so the vehicle can be used for a variety of tests

such as driving or braking traction, motion resistance, and steering maneuvers (Berliner and Shoop 1991, Shoop 1992). For the driving traction test performed in this study, the vehicle was placed in front-wheel drive and vehicle speed was held constant using the rear brakes while increasing torque was applied to the front axle. Thus, the tractive force was measured at both front wheels over a range of wheel slips, similar to the technique used by the U-G tester. At least eight tests were performed on each surface. Each test series was summarized by collating the averages, standard deviations, and averaged peak traction in a variety of graphs such as the traction curves shown in Figure A7.

SURFACES TESTED

Six conditions were tested, representing a variety of winter surfaces and a wide range of traction values. Air temperatures and snow depths and densities were measured as well as snow temperature at a depth of 2.5 cm or at the bottom of the surface snow layer. A sketch of the profile of each test surface is shown in Figure 1.

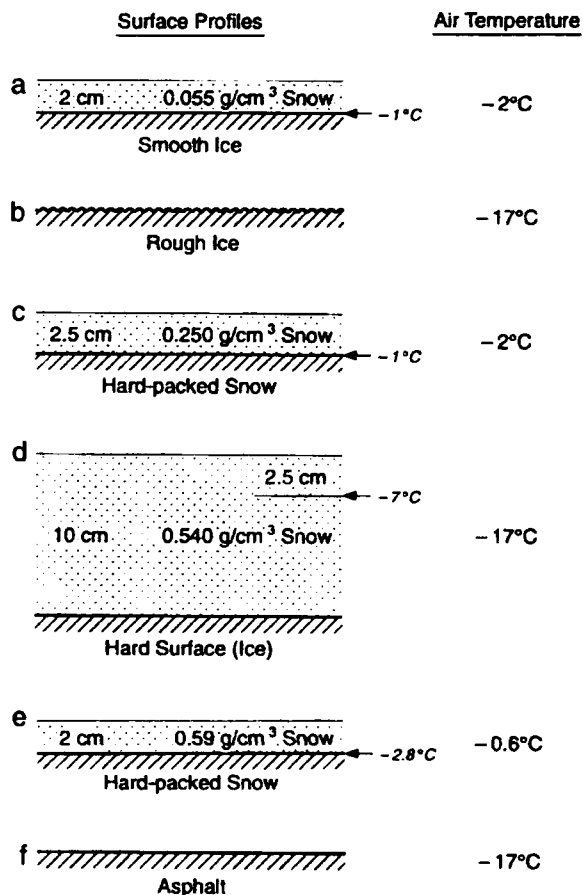


Figure 1. Terrain profiles.

REPORTING RESULTS AND TERMINOLOGY

Traction is a function of the relative movement between the wheel and the test surface, reported as skid (S [ISTVS 1977]), slip (i [ISTVS 1977]), or differential interface velocity (DIV), also called slip speed or longitudinal slip velocity (SAE 1992), where

$$\text{DIV} = V_w - V_v \quad (1)$$

$$S = (V_w - V_v) / V_v = \text{DIV} / V_v \quad (2)$$

$$i = (V_w - V_v) / V_w = \text{DIV} / V_w \quad (3)$$

V_v = velocity of the vehicle, and

V_w = (theoretical) longitudinal velocity of the wheel (i.e., rolling radius \times angular velocity of wheel).

The different terms developed from the way in which the test is run. Since a drawbar pull test is generally performed at constant engine rpm or constant wheel speed, the definition of slip in eq 3, with the constant wheel speed in the denominator, fully describes the test from 0 to 100% slip when the vehicle has been pulled to a stop. However, when running a constant vehicle speed test, such as is common for snow traction testers and instrumented vehicles, eq 2 (defined as *longitudinal slip* by SAE and as *skid* by ISTVS) more clearly defines the measurement because the constant vehicle speed is in the denominator. To add to the confusion, the SAE (1992) defines *slip ratio*, *longitudinal slip*, or *percent slip* the same as *skid* above; *wheel slip* the same as *slip* above; and *wheel skid* as an occurrence and not a mathematical expression. The use of longitudinal slip velocity or DIV clarifies the measurement, and its merit has been the topic of many discussions (Liston 1977). The remainder of this paper will refer to either slip or DIV using the definitions given in eq 1 and 3.

All these vehicles measure net traction and divide it by the measured vertical load to obtain a traction coefficient, μ (ISTVS 1977), also called net traction ratio (ASAE 1990). Because μ varies with slip, it is often reduced to a singular value based on its maximum, or it is averaged over a range of slip (or DIV). Several different methods of reporting traction, and their merits, are discussed in Domeck (1982) and Woehrle and Wozniak (1989). There are four reporting methods that are standard practice for these three approaches to traction testing:

1. *Maximum μ* is the singular maximum value or an average of a small amount of data (3%) surrounding the maximum.

2. *SAE μ* is an average of the μ obtained between a DIV of 3.2 and 24 km/hr (equivalent to a skid of 40 to 300% or a slip of 28 to 75% for vehicle speed of 8 km/hr). This represents the traction available at high slips rather than specifically optimum traction.

3. *μ at 12% slip* is the value occurring when the test wheel is slipping at 12% (DIV of 1.1 km/hr for vehicle speed of 8 km/hr).

4. *Averaged peak μ* represents the optimum tractive performance over a range of operating slips; it is calculated by taking the average of the top 20% of values.

There are other commonly used traction coefficients including that at 20% slip used by Waterways Experiment Station (based on numerous traction tests on soil where the traction curves leveled off to a nearly constant value by 20% slip), and at 15% slip used by agricultural engineers because it corresponds to the limiting slip for avoiding substantial soil compaction. Another useful representation of the traction-slip equation is *efficiency* (or work optimum coefficient [SAE 1967]), which is $\mu(1 - i)$.

FACTORS INFLUENCING TRACTION

The factors that affect traction can be placed into two groups: those variables related to the terrain and those related to the tire (Table 2).

Table 2. Factors influencing traction.

Terrain surface conditions	Tire conditions
Surface material	Inflation pressure
Macro texture	Size
(slope and obstacles)	Rubber compound
Micro texture	Temperature
Moisture	Tread design
Uniformity	Load
Temperature	Structure

Each of these variables affects not only the magnitude of traction but also influences the shape of the μ -slip curve. For example, traction on ice is usually lower than traction on soils, and the shape of the μ -slip curve can be very different. Where a traction curve on soil may be a smooth hyperbolic shape, the traction curve on ice usually has a strong sharp peak at low slips and then very abruptly decreases to a constant value. The idealized μ -slip curves shown in Figure 2 illustrate how curves may vary with terrain.

Even on the same surface material, the traction curve shape changes with the tire type, as seen in Figure 3 for three radial tire designs on the same

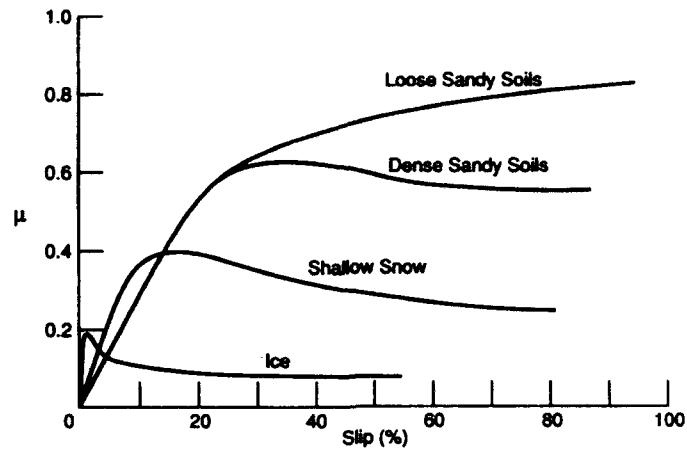


Figure 2. Generalized μ -slip curves for different surface materials.

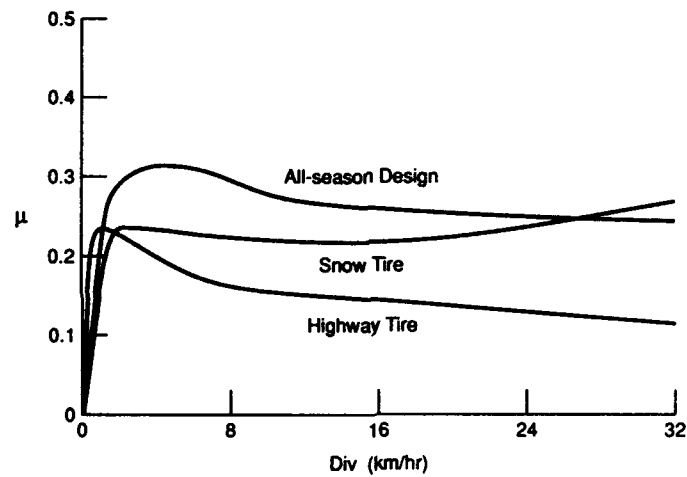


Figure 3. Variation in μ -slip curves from different tire designs.

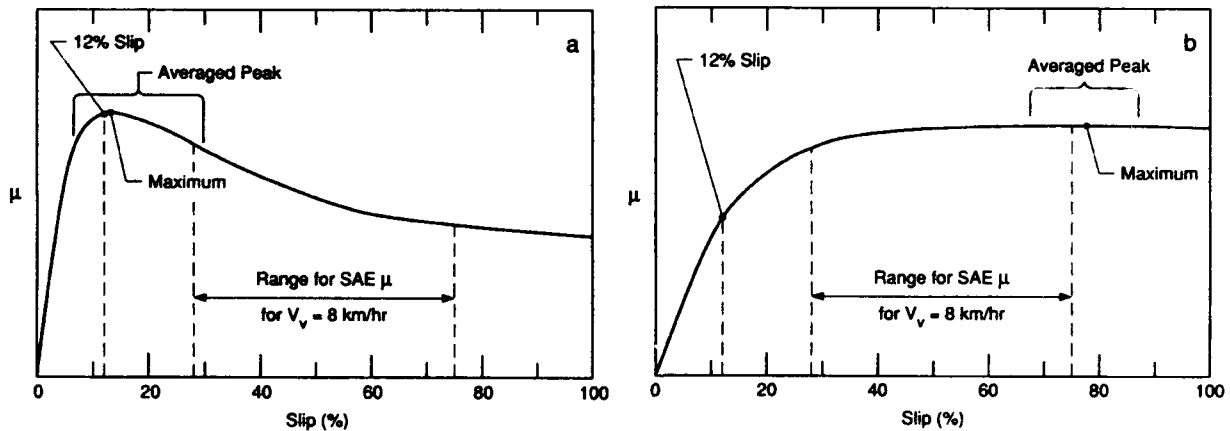


Figure 4. Location and relative value of the different traction coefficients based on the calculation method and shape of the μ -slip curve.

medium-packed shallow snow (Domeck 1982). While the standard highway tire and all-season design have a definite peak traction coefficient followed by a decreasing slope in the curve, the snow tire shows no initial peak and maintained a high traction coefficient (even increasing slightly) at high DIVs.

The shape of the curves is indicative of the behavior of the surface material. Generally, behavior can be related to whether surface material is loose or compact and therefore fails with compactive or dilatant behavior under the stress applied by the tire. Similarly, a peak in the traction curve may indicate adhesive or apparent cohesive behavior, due to frictional interlocking of terrain particles or interlocking of the terrain and the tire tread.

As the curve shape changes, the peak occurs at different values of slip. For instance, with a peaked curve typical of snow, ice, and dense granular soils (Fig. 4a), the SAE μ is lower than the maximum μ . On the other hand, for conditions where traction increases, or remains constant with increasing slip, the maximum μ may equal SAE μ (Fig. 4b).

RESULTS

Traction curves for each surface

The shape and magnitude of traction curves is the result of a complex interaction between the tire and the terrain, and the curve shapes obtained in this study varied accordingly. Characteristic DIV curves for each of the six surfaces tested, obtained with the same tire and loading, are shown in Figure 5. The curves were gathered using the CIV, with the exception of the snow test section data from the U-G traction tester. The similar curve shape for the groomed snow test section and the snow road reflect the similar terrain profiles of these two surfaces (refer to Fig. 1). The lower values for the snow road are a direct result of the lower snow density and higher temperature (much closer to melting temperature).

While the initial curve is the same for both ice surfaces, with the rough ice slightly greater, the small amount of snow on the smooth ice has a beneficial effect on traction that is not reflected in any of the methods for calculating μ because it occurs at very high DIV. This gentle increase was seen in all eight

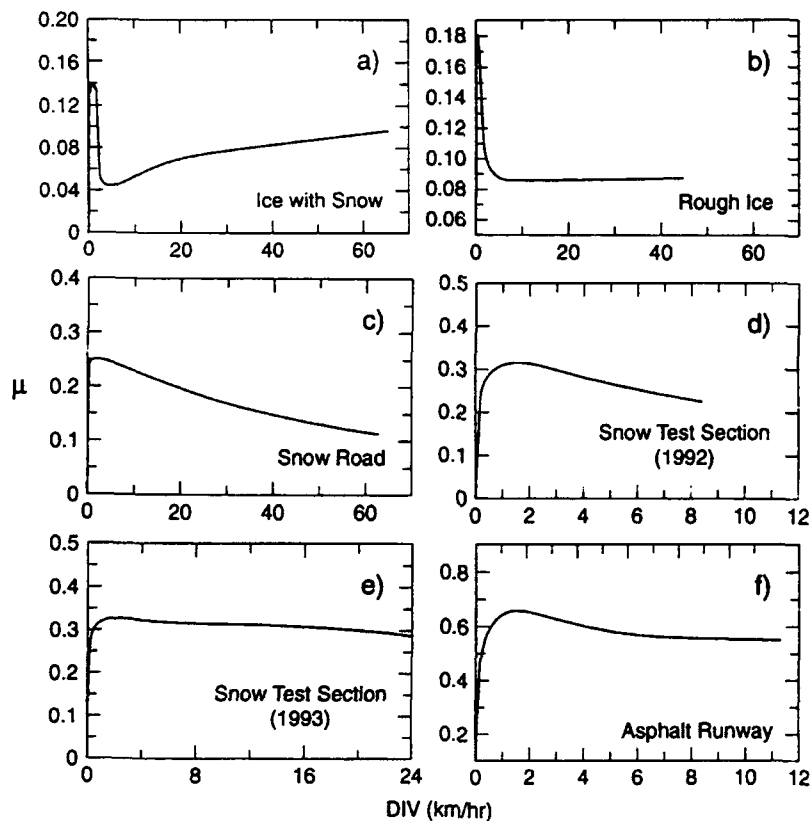


Figure 5. Typical μ -DIV curves for six winter surfaces.

tests on the ice with snow but was not seen when testing on bare ice. The distinctive shapes of these curves directly affect the relative value of μ , depending on the particular calculation method, as shown in Figure 4.

Traction coefficients

The Saab friction tester measures only the μ at 12% slip, and the U-G tester routinely reports both the SAE μ and a maximum (peak) μ . The CIV routinely reports an averaged peak traction value, but for this study the data were also used to calculate the other traction coefficients. A summary of the results for all three vehicles on each of the surfaces tested is assembled in Table 3. Values reported are for net traction. The motion resistance measured with the CIV can be used to obtain gross traction for the CIV and U-G, which used the same tire and tire loading conditions. This is done in Appendix B. Comparisons of these traction coefficients with other

measurements on similar surfaces and with predicted values are also given in Appendix B.

The bar chart (Fig. 6) shows the traction coefficients for each of the surfaces, grouped by vehicle and data reduction method. Arranging the surfaces, from slippery (smooth ice) to tractive (asphalt runway), results in the same ranking, independent of test vehicle and data reduction scheme. The exception is the two snow test sections measured with the U-G, whose curve shape changed from gently decreasing in 1992 (Fig. 5), resulting in low SAE, to relatively flat in 1993 where Max. and SAE are nearly equal.

To compare the four different μ calculations, the CIV data are shown in Figure 7 grouped by test surface. For all surfaces, the maximum μ is greatest, followed by the averaged peak and 12% slip values, and the SAE μ is consistently lowest. Aside from the 1993 snow test section, which had a relatively flat μ -DIV curve, the range of the μ values becomes pro-

Table 3. Net traction coefficients.

	Uniroyal-Goodrich		Saab	CIV*			
	Max. (3%)	SAE	12% slip	Max. (singular)	Avg peak	12% slip	SAE
a. Smooth ice with snow	—	—	0.03	0.14	0.12	0.09	0.05
b. Rough ice	0.18	0.08	0.09	0.18	0.15	0.13	0.08
c. Snow road	—	—	0.13	0.31	0.26	0.25	0.18
d. Snow test section ('92)	0.36	0.19	0.24	—	—	—	—
e. Snow test section ('93)	0.34	0.31	—	0.36	0.32	0.31	0.30
f. Asphalt runway	0.69	0.57	0.58	0.72	0.64	0.57	0.51

* CRREL Instrumented Vehicle.

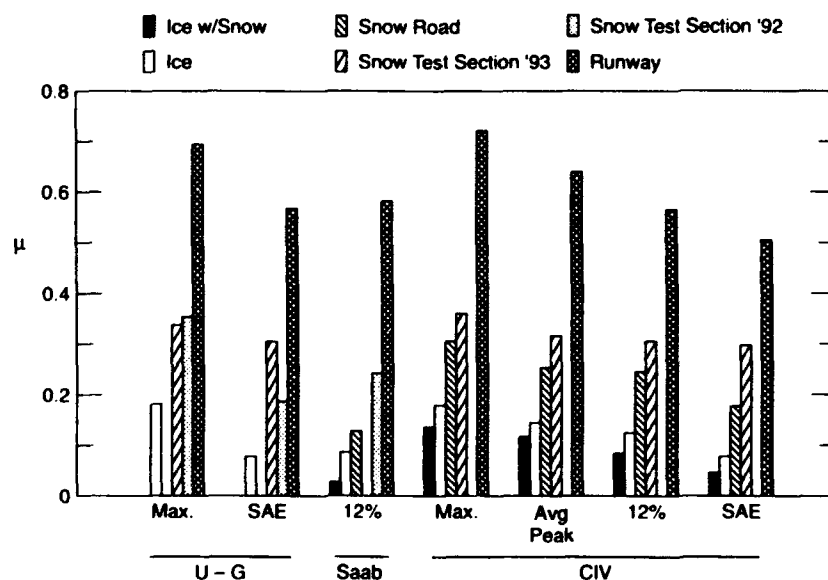


Figure 6. Comparison of surface traction by test method and reporting method.

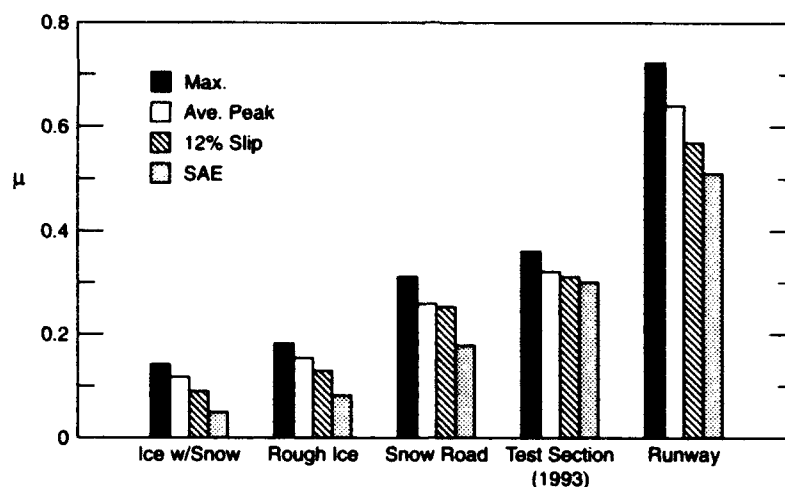


Figure 7. Comparison of four methods of reporting traction coefficients using CIV test data.

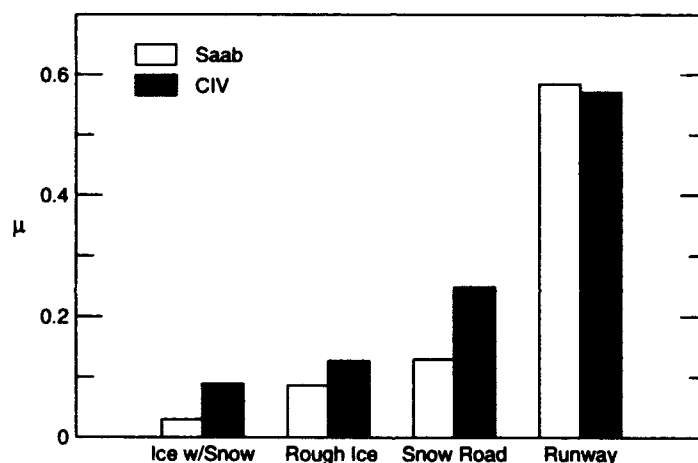


Figure 8. Comparison of the test data between the Saab and the CIV.

gressively larger as the operating surface becomes more tractive. The wide range of traction coefficients on the airport runway could also be caused by scatter in the data due to small patches of hard-packed blown snow.

Accurate comparisons between the vehicles are possible when the same μ reporting method is used. In Figure 8, μ at 12% slip measured with the CIV and the Saab reflect the contrast in the test tire characteristics (Table 1) and the fact that the Saab test uses braking traction while the CIV uses driving traction. The CIV tire has higher traction on snow (by 48%) and ice (30 to 67%), where the aggressive tread pattern and rubber compound are more effective, and the aircraft tire performs best on the runway, as per its design.

Figure 9 compares the U-G tester and the CIV, reporting both maximum and SAE μ . The vehicles

measure the same values for the ice surface and differ by only 3 to 11% on the snow test section and the asphalt runway. Because the tire conditions were the same, this small difference is likely due to unavoidable experimental variations (e.g., snow patches on the runway surface).

Considering the differences and similarities of the vehicles and test techniques, one might now ask "which is best?" Certainly, the agreement between the vehicles is very encouraging when the effects of tire design are considered. At the same time, there is a large difference between the traction coefficient based on the μ calculation technique (particularly for the more tractive surfaces), although the relative ranking of surfaces is consistent. The best traction value is that which most closely reflects the specific application. Because the Saab measures traction to assess safe aircraft braking, traction at 12% braking

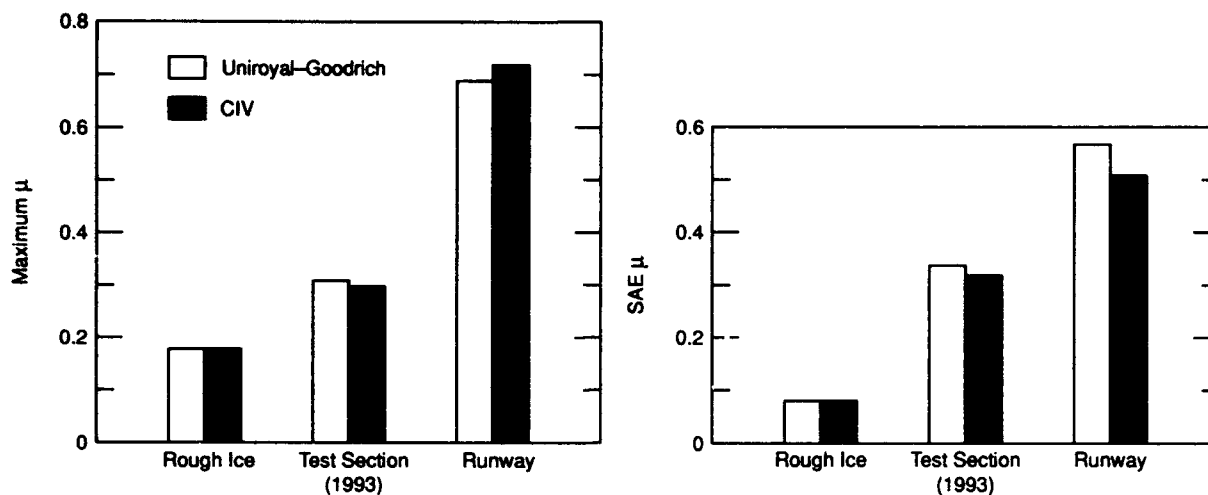


Figure 9. Comparison of μ measured with the Uniroyal-Goodrich traction tester and the CRREL Instrumented Vehicle.

slip is logical. The SAE μ represents a conservative estimate of traction available to an untrained driver who tends to operate at high slip when faced with difficult or slippery surface conditions. Conversely, the peak μ represents traction at the optimum performance. The comparison and agreement between test equipment and methods enhances possibilities for future cooperation and collaboration among the various traction testing communities. It also frees the test or research engineer to choose the best test method, reduce the data to meet the application, and be confident that the results can be compared with other test methods.

CONCLUSION

Three very different state-of-the-art instrumented vehicles were compared in side-by-side traction tests on six winter surfaces. The CRREL Instrumented Vehicle is a versatile instrumented vehicle used for vehicle mobility research, the Uniroyal-Goodrich traction tester is used for commercial tire testing on snow using the SAE standard method, and the Saab friction tester is the most sophisticated of the several FAA-approved methods for measuring runway friction. Four methods of reducing the μ -slip (or DIV) curves to a representative traction coefficient were used. The following points summarize the findings of this investigation:

1. Each surface has a distinctively shaped μ -DIV curve, with similar surfaces yielding similar curve shapes (Fig. 5). Because of the differences in curve shapes, the magnitude of peak μ and its relationship to slip-specific μ values (i.e., 12% slip and SAE μ) varies with the surface material. Even so, the maximum μ is consistently greatest, followed by the averaged peak and 12% slip values, and the SAE μ is consistently lowest.

imum μ is consistently greatest, followed by the averaged peak and 12% slip values, and the SAE μ is consistently lowest.

2. The test surfaces covered a wide range of traction coefficients, from 0.03 on smooth ice to 0.72 on the asphalt runway. The ranking of the test surfaces, from slippery to tractive, was generally the same regardless of the test vehicle or data reduction scheme (Table 3, Fig. 6).

3. With the significant differences among the methods of reporting μ (particularly for the more tractive surfaces), the best value is that which most closely reflects the specific application. The maximum and averaged peak values indicate optimum tractive performance, but to assess safe aircraft landing, it is logical to measure traction at 12% braking slip. For comparing the snow traction of various tires, the SAE μ represents a conservative estimate of traction available to the untrained driver who tends to operate at high slip when faced with difficult or slippery surface conditions.

4. Using the same μ reporting method, the agreement between the CIV and the U-G tester (using the same test tire) was consistently excellent (Fig. 9). However, differences between the Saab and the CIV (Fig. 8) are based on tire performance. The aircraft tire (Saab) performed better on the runway, and the all-season tire (CIV) performed better on snow and ice.

The results of this study form the basis for comparison and collaboration between the various traction testing communities. This information may allow the development of a standard practice for traction testing and reporting that can be used by all traction testers.

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APPENDIX A: VEHICLE INSTRUMENTATION AND SAMPLES OF GRAPHIC OUTPUT

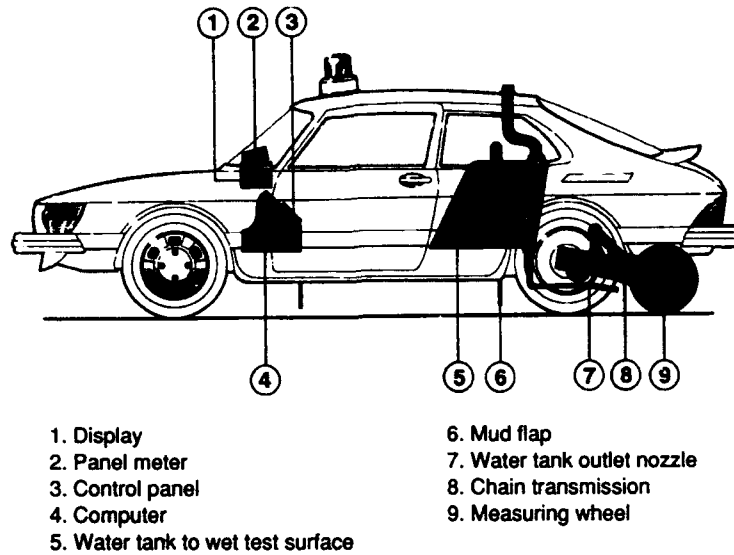


Figure A1. The Saab friction tester.

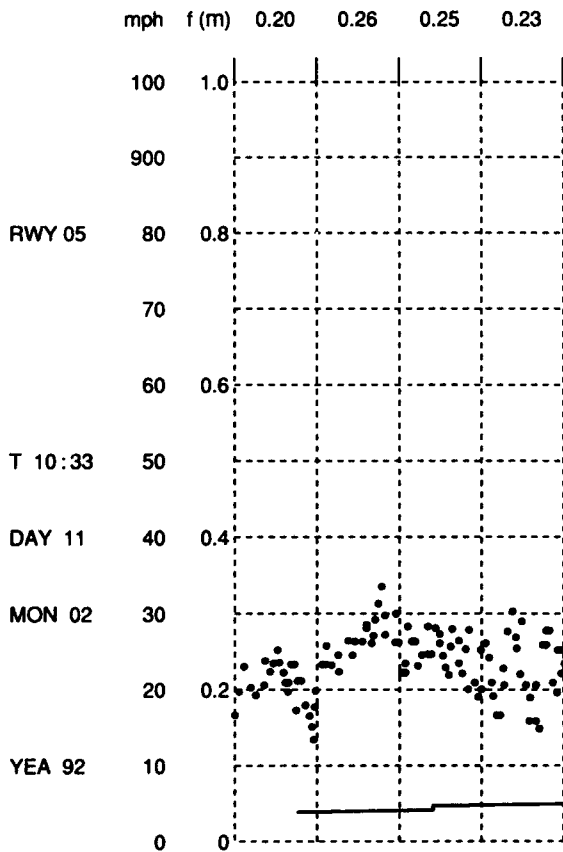
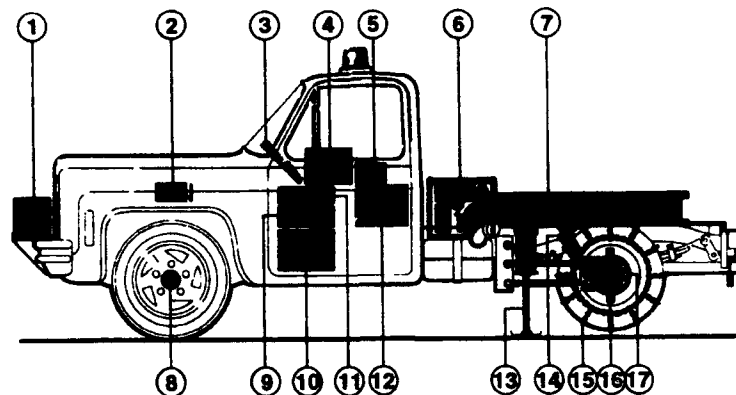


Figure A2. Typical data from a Saab friction test on groomed shallow snow. Friction was measured over a distance of 121 m (400 ft) and averaged every 33.3 m (100 ft), as printed at the top of the graph. The vertical axis is vehicle speed (solid line) and friction (circles), and the horizontal axis is distance (each block is 100 ft).



- | | |
|---|--|
| 1. Box on left front for weights to unload right rear | 11. 20 Mb hard drive |
| 2. Computer-controlled throttle | 12. Daytronic Model 10KG data acquisition and signal conditioner |
| 3. Keyboards | 13. Self-contained hydraulic jack |
| 4. Data acquisition CRT | 14. Air shocks to adjust vehicle attitude |
| 5. HP ink-jet printer | 15. Tire chain to prevent slip of left rear |
| 6. 2 kW Honda 115 Vac power generator | 16. Right rear housing contains orthogonal load cell to measure tire loads |
| 7. Static load containment | 17. Right rear wheel assembly contains optical encoder to measure test tire velocity |
| 8. Optical encoder to measure ground velocity | |
| 9. HP 9000 Series computer | |
| 10. HP CRT | |

Figure A3. The Uniroyal-Goodrich traction tester (property of Michelin Americas Research and Development Corporation).

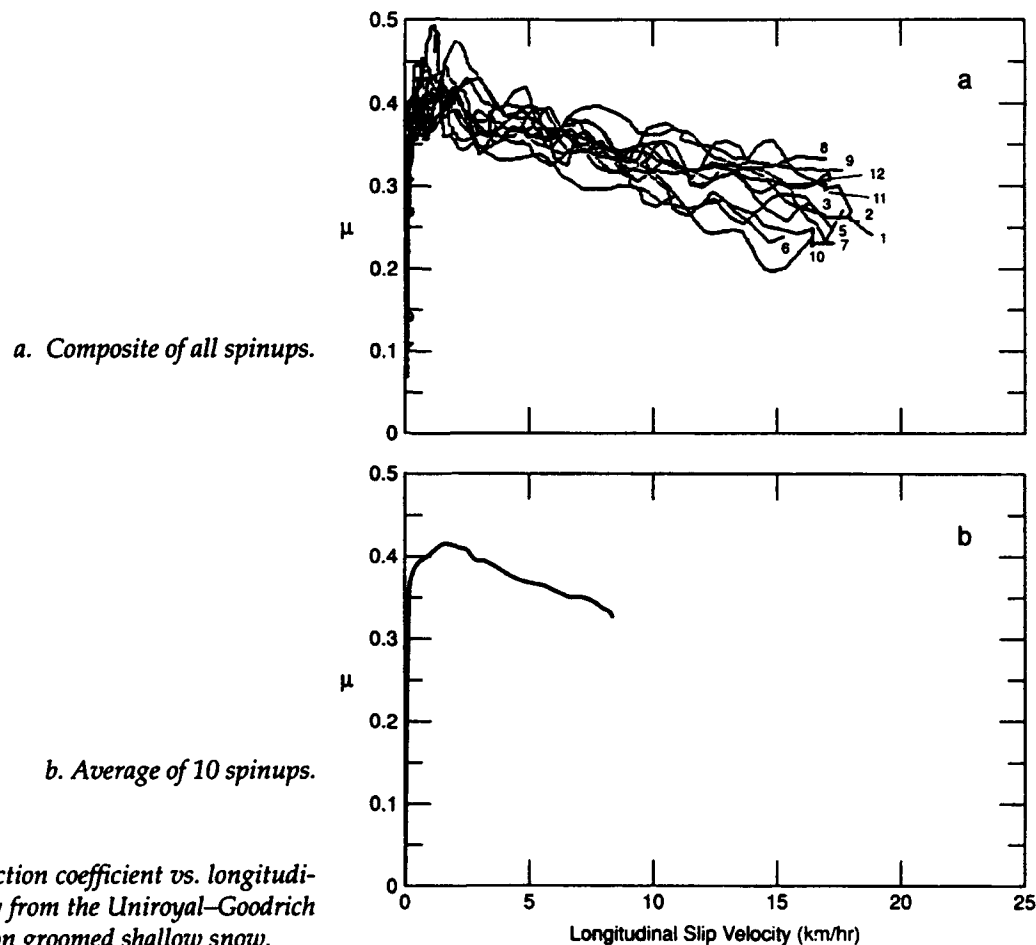


Figure A4. Traction coefficient vs. longitudinal slip velocity from the Uniroyal-Goodrich traction tester on groomed shallow snow.

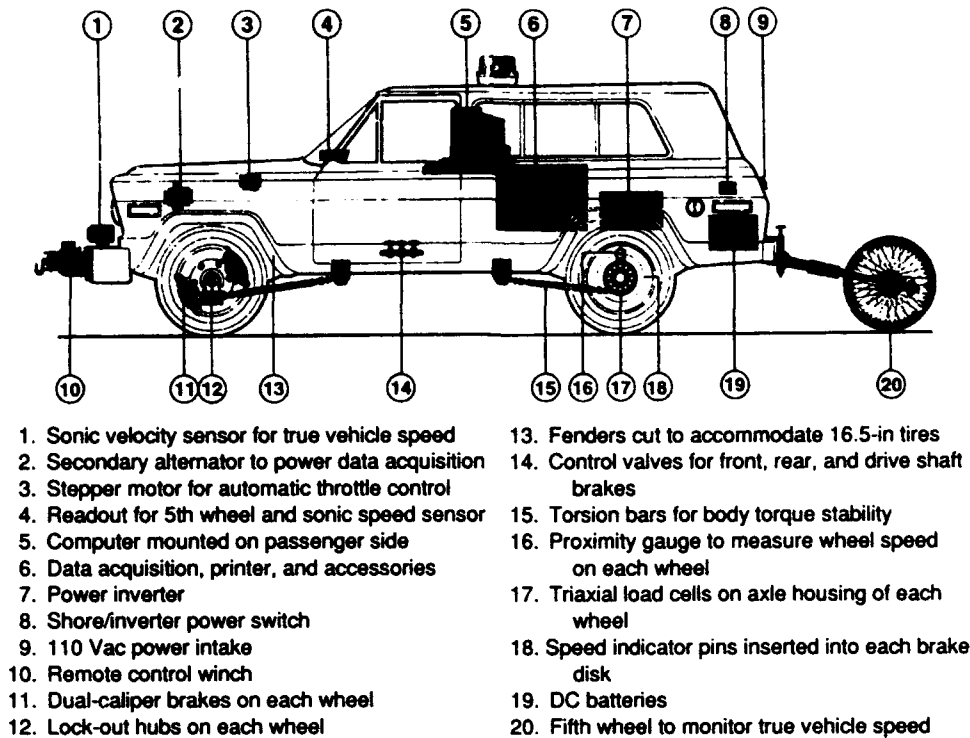


Figure A5. The CRREL Instrumented Vehicle.

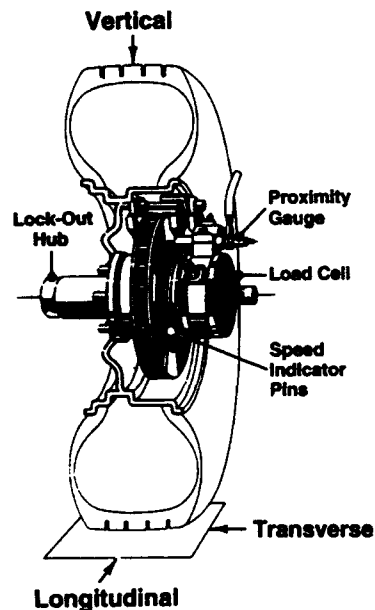


Figure A6. Configuration of speed sensors and axle-mounted load cells.

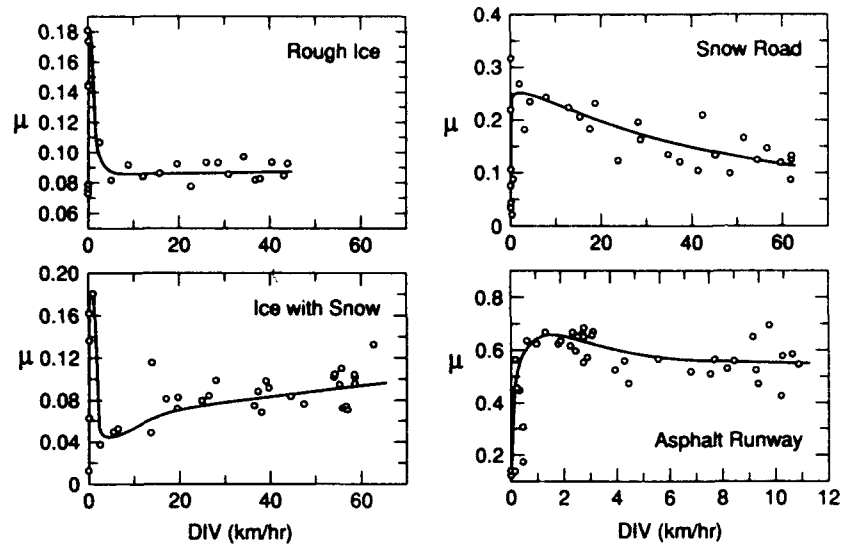


Figure A7. Typical graphical output from the CRREL Instrumented Vehicle for four of the test surfaces.

APPENDIX B: COMPARISON OF MEASURED TRACTION COEFFICIENTS WITH PUBLISHED AND PREDICTED VALUES

Predicted gross traction based on equations given in Richmond et al. (1990) is in good agreement with measured gross traction on similar surfaces (Table B1). The equations used to calculate measured gross traction and predicted gross traction are given below. Comparisons of published and predicted traction coefficients for ice and shallow snow are shown in Table B1 and Figures B1 and B2.

Traction prediction equation for undisturbed snow:

$$T_g = 0.851 N^{0.823}$$

for hard-packed snow:

$$T_g = 0.321 N^{0.97}$$

for undisturbed snow over ice:

$$T_g = 0.127 N^{1.06}$$

where T_g is gross tractive stress and N is the normal stress under the tire or track (kPa).

Gross Traction:

$$T_g = T_n + MR_{\text{terrain}}$$

where T_g is gross traction, T_n is net traction, and MR_{terrain} is the external motion resistance attributable to deformation of the terrain material.

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Table B1. Measured, published, and predicted traction coefficients.

	T_n^a	T_n^b published	T_n^c rules of thumb	MR_{terrain}^d	T_g measured	T_g predicted
Smooth ice with snow	0.12	0.08, 0.11	—	0.022	0.14	0.17
Ice	0.15	0.12→0.28	0.12	0.0015	0.15	—
Snow road	0.26	—	0.20	0.03	0.29	—
Snow test section ('93)	0.32	0.28	0.20	0.009	0.32	0.28

a CIV average peak from Table 3.

b Published values on similar surfaces (also measured with CIV).

Values for buffed and steamed ice at -10°C and -3°C (Blaisdell and Borland 1992).

Range of values for "natural" ice (Blaisdell 1983).

CIV with same tire and tire loading in 6 cm of 0.59 g/cm^3 snow (Richmond et al. 1990).

c Society of Mining Engineers (1973) traction values used to estimate haulage on ice and packed snow.

d Measured during this study (based on subtracting hard surface motion resistance from total motion resistance measured using a static vehicle calibration).

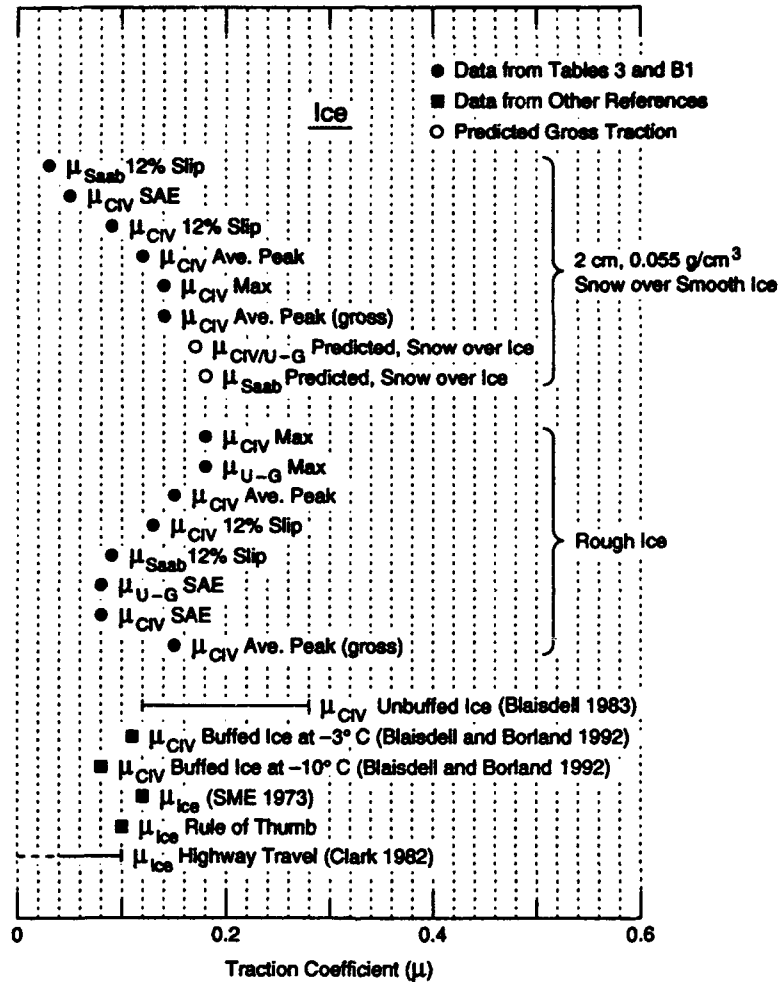


Figure B1. Measured, published, and predicted values of traction on ice.

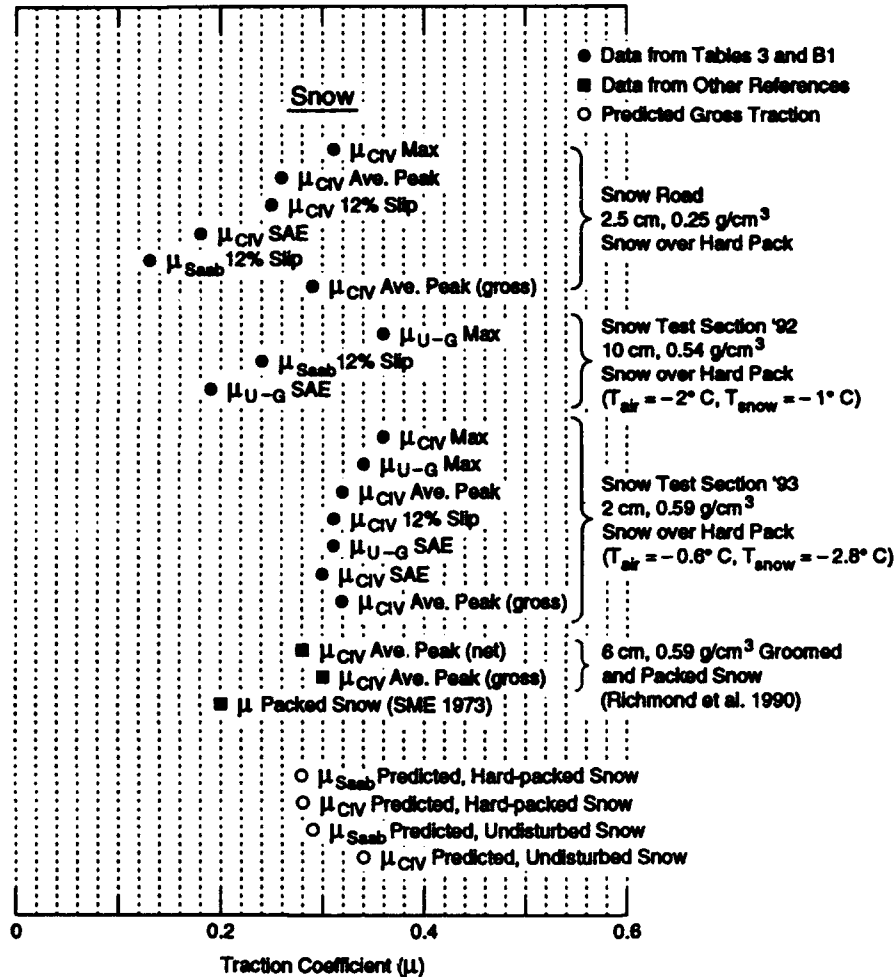


Figure B2. Measured, published, and predicted values of traction on shallow groomed snow.

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